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(54) Implantable pacemaker having adaptable AV interval for cardiomyopathia treatment

Implantierbarer Herzschrittmacher mit anpassbarem AV-Intervall zur Behandlung von Kardiomyopathie

Stimulateur cardiaque implantable avec interval AV adaptable pour le traitement de cardiomyopathie

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Description

[0001] The present invention relates to implantable medical devices, and more particularly, to an implantable pacemaker that automatically adapts its atrial-ventricular (AV) delay to maximize the cardiac output for patients having a cardiomyopathy.

[0002] The heart is a pump that pumps life-sustaining blood throughout the body of the patient. The human heart comprises a left side and a right side, with each side having a first chamber, known as the atrium, and a second chamber, known as the ventricle. The atrium receives blood returning from other body locations. At an appropriate time, determined by the sinoatrial (SA) node, an electrical stimulus is provided that causes the muscle tissue surrounding the atrium to depolarize. Depolarization of the atrial muscle tissue is manifest by the occurrence of an electrical signal known as the P-wave. Immediately following the P-wave, the atrial muscle tissue physically contracts, forcing the blood held in the atrium through a one-way valve into the ventricle. The SA node stimulus that caused the atrium to depolarize also travels to the ventricle through the atrioventricular (AV) node and the atrioventricular (AV) bundle. The AV node is a mass of modified heart muscle situated in the lower middle part of the right atrium. It receives the impulse to contract from the sinoatrial node, via the atria, and transmits it through the atrioventricular bundle to the ventricles. The AV bundle is a bundle of modified heart muscle fibers (Purkinje fibers) that pass from the AV node forward to the septum between the ventricles, where it divides into right and left bundles, one for each ventricle. The fibers thus transmit the SA node stimulus from the atria, via the AV node, to the ventricles. However, as the SA node stimulus travels through the AV bundle, it is delayed by an amount commensurate with the same time it takes the blood to physically flow from the atrium to the ventricle.

[0003] After the delay through the AV bundle, which delay may be referred to as the natural conduction time of the heart, the SA node stimulus arrives at the ventricular muscle tissue, causing it to depolarize. Depolarization of the ventricular muscle tissue is manifest by the occurrence of an electrical signal known as the R-wave (sometimes referred to as the QRS complex). Immediately following the R-wave, the ventricular muscle tissue physically contracts, forcing the blood held therein through one or more arteries to various body locations. In this manner, then, the heart "beats" or pumps blood by having the atria contract at a rate determined by the SA node, and after the natural conduction time, by having the ventricles contract. After a longer delay, when the atrium has refilled with blood returning from throughout the body, the process repeats.

[0004] The heart of a typical healthy patient may beat 60-70 times per minute when the patient is at rest. When the patient is undergoing significant physiological stress, as occurs, e.g., during physical exercise, the rate at which the heart beats, the "heart rate," increases significantly, e.g. up to 150-170 times per minute. The above-described process wherein the atria and ventricles sequentially depolarize and contract in order to pump blood, and get ready to depolarize again, is referred to herein as the "cardiac cycle." A given cardiac cycle thus includes one R-wave (or equivalent ventricular activity evidencing depolarization of the ventricles) and one P-wave (or equivalent atrial activity evidencing depolarization of the atria). The length of the cardiac cycle (which represents the period of the heart rate) may be measured as the time interval between successive P-waves or R-waves, although R-waves are usually used because they are easier to detect.

[0005] A pacemaker is an implantable medical device that monitors the activity of the heart for the occurrence of P-waves and/or R-waves, and steps in with electronically generated stimuli, when needed, to force the depolarization of the atria and/or ventricles. A pacemaker-generated stimulus that is delivered to the atrium is referred to herein as an "A-pulse." A pacemaker-generated stimulus that is delivered to the ventricle is referred to herein as a "V-pulse." Most pacemakers are configured to provide an A-pulse and/or V-pulse only if a prescribed period of time has elapsed without the occurrence of a P-wave and/or an R-wave, i.e., without the occurrence of natural heart beats.

[0006] The prescribed period of time used by the pacemaker between contraction of the ventricle and contraction of the atrium is generally referred to as the V-A Interval, or the atrial escape interval. For most dual-chamber pacemaker modes of operation, only if a P-wave does not occur during the atrial escape interval will the pacemaker step in at the conclusion of such interval and generate an A-pulse.

[0007] The prescribed period of time used by the pacemaker between contraction of the atrium and contraction of the ventricle is referred to as the A-V Interval, or sometimes it is called the "AV Delay." The pacemaker, for most dual-chamber modes of operation, generates a V-pulse only if the AV Delay elapses without the occurrence of an R-wave.

[0008] In the above-described manner, the heart is thus afforded as much time as possible to beat on its own before the electronically-generated stimuli of the pacemaker are delivered to the heart, causing it to beat at the rate set by the pacemaker.

[0009] Heretofore, most cardiac patients using a pacemaker have suffered from at least one of various cardiac conditions or diseases that affect either the ability of the SA node to maintain and sustain a satisfactory heart beat rate (hereafter "rate problems"), or the ability of the AV node or the AV bundle to conduct a suitable stimulus to the ventricle (hereafter "conduction problems"). Advantageously, both rate problems and conduction problems lend themselves well to a pacemaker solution because the underlying cardiac muscle tissue is in place and is capable of responding to the electron-

ically-generated stimuli produced by the pacemaker.

[0010] Unfortunately, there remain a significant number of patients that suffer from one or more conditions that cannot be characterized as either rate problems or conduction problems. One such problem is known as hypertrophic cardiomyopathy. Another is known as dilated cardiomyopathy. While there are medical or clinical differences between these two forms of cardiomyopathy, for purposes of the present invention they may be considered the same problem, and will be referred to hereafter as simply "cardiomyopathy."

[0011] In general, a patient suffering from cardiomyopathy experiences a significant reduction in cardiac output because the heart muscle is unable to perform its function of contracting in response to the SA node stimulus. By "cardiac output," it is meant the ability of the heart to efficiently pump blood. Thus, a patient suffering from cardiomyopathy will generally not have as much blood pumped per heart beat (stroke volume) as may be needed. Cardiomyopathy patients are referred to as being moderately to severely symptomatic of low cardiac output syndrome. The only treatment for low cardiac output syndrome, up to now, has been heart transplantation. Disadvantageously, heart transplantation is not a viable solution for most patients. Not only are hearts suitable for transplant difficult and expensive to secure, but even when secured, a very dangerous and complicated surgery must follow in order to successfully perform the transplantation operation. What is thus needed is an alternative to heart transplantation for patients suffering from low cardiac output syndrome.

[0012] It has recently been proposed to implant a dual-chamber pacemaker in patients suffering from low cardiac output syndrome and to configure such pacemaker to provide PV or AV pacing. During PV or AV pacing, the pacemaker delivers a V-pulse to the ventricles a programmed delay after the occurrence of an atrial event, which atrial event could be either the occurrence of a P-wave or the delivery of an A-pulse. Advantageously, by forcing a ventricular contraction prior to the occurrence of an R-wave, i.e., prior to natural depolarization of the ventricles, the cardiac output of patients suffering from cardiomyopathies may be significantly improved. Such improvement appears to result because the ventricular stimulus --a V-pulse delivered by the pacemaker-- is applied to the ventricular tissue at a different cardiac location (at the location of the ventricular lead tip electrode, which location is usually in the apex of the right ventricle) than is the natural stimulus when received through the SA node.

[0013] PV or AV pacing is only effective, however, when the V-pulse is delivered to the ventricular tissue before the occurrence of an R-wave, i.e., before the ventricular tissue depolarizes. As soon as the ventricular tissue depolarizes, it becomes refractory, and will not respond to a V-pulse, until such time as it repolarizes. It is thus necessary, if AV or PV pacing is to be used, to set the AV (or PV) interval of the pacemaker to a value that is less than the patient's normal conduction time. Unfortunately, heretofore, this requirement has forced the AV (or PV) interval to be set to very short values, i.e., between 80 and 120 msec, because during exercise (or other periods of physical activity or physiological stress) the patient's native conduction time may shorten significantly. Thus, in order to guarantee that the pacemaker will always pace the ventricles, i.e., in order to assure that the V-pulse is delivered to the ventricular tissue at a time when it is not refractory, the AV (or PV) interval must be set to an interval that is shorter than any native conduction interval that might exist in any given patient at any given time.

[0014] Disadvantageously, setting a very short programmed AV (or PV) interval may adversely affect cardiac output because it may force ventricular contraction well before the ventricles have had sufficient time to be filled with blood from the atrium. Thus, what is needed for patients suffering from a cardiomyopathy is a pacemaker that paces the ventricles at a time in the cardiac cycle that is always less than the natural conduction time, i.e., at a time that is prior to the occurrence of an R-wave, but that is not so much less than the natural conduction time so as to adversely affect cardiac output. That is, what is needed is a pacemaker that automatically sets its internally-generated AV and/or PV intervals to be just short of the patient's native conduction time, thereby assuring that the AV (or PV) interval is sufficiently long to allow the blood to physically move from the atrium to the ventricles; yet remains sufficiently short to always be less than the patient's native conduction time, thereby assuring that the V-pulse is not delivered when the ventricular tissue is refractory.

[0015] The present invention advantageously addresses the above and other needs.

[0016] In addition, EP-A-450387 discloses a pacemaker which has a paced AV delay that is automatically adjusted to include patient variations in latency conduction. An AV timer designed to provide a programmed AV interval starts its timing operation at the generation of an atrial pulse and re-starts the timing operating at the occurrence of the evoked atrial potential.

[0017] According to the invention, there is provided a dual-chamber pacemaker for controlling ventricular pacing in order to increase cardiac output in a patient suffering from a cardiomyopathy by preemptively stimulating the ventricular channel, comprising: an atrial channel and a ventricular channel; an atrial sense amplifier that senses a P-wave in the atrial channel, the P-wave representing natural atrial activity; a ventricular sense amplifier that senses an R-wave in the ventricular channel, the R-wave representing natural ventricular activity; pulse generator means for generating a ventricular stimulation pulse (V-pulse) in the ventricular channel and an atrial stimulation pulse (A-pulse) in the atrial channel, the sensing of a P-wave or the generating of an A-pulse, whichever occurs first, representing atrial activity; and timing means arranged to define an

AV time interval as the time interval between atrial activity and the generation of the V-pulse, characterised in that the timing means further being arranged to measure a natural conduction time interval as the time period between atrial activity and the sensing of an R-wave; the timing means also being arranged to set automatically the AV time interval to a value that is less than the natural conduction time interval, whereby the pulse generator generates the V-pulse prior to the occurrence of natural ventricular activity in order to stimulate preemptively the ventricular channel, thereby increasing cardiac output.

[0018] The present invention may therefore provide a dual-chamber implantable pacemaker wherein the natural conduction time of a patient is measured, and the AV (or PV) interval of a dual-chamber pacemaker implanted in the patient is automatically set to a value just less than the measured natural conduction time. A ventricular stimulation pulse (V-pulse) is generated at the conclusion of the pacemaker-defined AV (or PV) interval if no natural ventricular activity (an R-wave) is sensed during such AV (or PV) interval. Because the AV (or PV) interval is automatically set to a value just less than the natural conduction time, a V-pulse will almost always be applied to the ventricular muscle tissue at a time when such muscle tissue is capable of responding thereto, i.e., at a time when the tissue is not refractory. In the event that an R-wave does occur, signaling that the natural conduction time of the patient is decreasing (as might occur, for example, if the patient is exercising), the occurrence of the R-wave provides a new measure of the natural conduction time, which thereafter affords a basis for further adjusting the AV interval.

[0019] The pacemaker-defined AV interval begins upon the delivery of an atrial stimulation pulse (A-pulse) by the pacemaker. Similarly, the pacemaker-defined PV interval begins upon sensing natural atrial activity (a p-wave) by the pacemaker. The natural conduction time measured by the pacemaker comprises the time between atrial activity (whether a sensed p-wave or a delivered A-pulse, whichever occurs) and subsequent natural ventricular activity (an R-wave). The method of operating such a pacemaker thus includes:

> (1) measuring the natural conduction time t_{AR}, of the patient in a given cardiac cycle; and (2) setting the AV (or PV) interval of the pacemaker, for use in subsequent cardiac cycles, to a value that is a prescribed amount, e.g, 20-30 msec., less than t_{AR}.

[0020] Thus, in a preferred form, the pacemaker includes a timing counter, or equivalent, that is initiated upon the occurrence of each atrial event, whether a p-wave or an A-pulse. The atrial event also starts the AV (or PV) interval of the pacemaker. If an R-wave occurs in the cardiac cycle before the termination of the AV (or PV) interval, then the timing counter stops, with the count held therein providing a measure of the natural conduction time, t_{AR}. The AV (or PV) interval set by the pacemaker is then immediately and automatically adjusted to a new value that is the prescribed amount less than t_{AR}. The new adjusted value of AV (or PV) is then used for the next cardiac cycle. In this manner, the AV (or PV) interval is adaptively adjusted, as required, to always be less than the natural conduction time of the patient.

[0021] If a prescribed number of consecutive cardiac cycles ensue without the occurrence of an R-wave, then the value of the AV (or PV) interval is gradually increased, in order to incrementally return it to its original value.

[0022] A dual-chamber pacemaker made in accordance with the present invention includes an atrial channel and a ventricular channel. An atrial sense amplifier senses the occurrence of natural atrial activity (a P-wave) in the atrial channel. A ventricular sense amplifier similarly senses the occurrence of natural ventricular activity (an R-wave) in the ventricular channel. An atrial pulse generator generates an atrial stimulation pulse (A-pulse) in the atrial channel in the absence of a sensed P-wave by the atrial sense amplifier within an AV time interval. Similarly, a ventricular pulse generator generates a ventricular stimulation pulse (V-Pulse) in the ventricular channel in the absence of a sensed R-wave by the ventricular sense amplifier within an atrial escape interval. A control circuit coupled to both the atrial and ventricular channels defines the AV time interval and the atrial escape interval. The AV time interval begins upon the sensing of atrial activity in the atrial channel, where atrial activity may be either a P-wave or the generation of an A-pulse, whichever event occurs. The atrial escape interval begins upon the sensing of ventricular activity in the ventricular channel, where ventricular activity may be either an R-wave or the generation of a V-pulse, whichever event occurs first. The control circuit of the pacemaker includes timing means for measuring a natural conduction time interval as the time period between atrial activity in the atrial channel and the sensing of an R-wave in the ventricular channel. In accordance with the present invention, the control circuit automatically decreases the AV time interval to a value that is less than the natural conduction time interval by a prescribed amount, which decreased AV time interval value is not to be less than a minimum AV time interval value.

[0023] Hence, in the absence of a decreasing natural conduction time interval, the pacemaker of the present invention generates a V-pulse in the ventricular channel prior to the occurrence of an R-wave, thereby providing needed therapy for patients who most always need a V-pulse, e.g., patients suffering from a cardiomyopathy. Further, in the presence of a decreasing natural conduction time interval, the pacemaker of the invention automatically decreases the AV time interval to a value that is less than the shortest conduction time interval.

[0024] Moreover, in accordance with a preferred form

of the invention, the control circuit of the dual-chamber pacemaker automatically increases the AV time interval by a prescribed amount in the event a prescribed number of consecutive cardiac cycles occur without an R-wave having been sensed by the ventricular sense amplifier. Thus, the AV time interval will never remain adjusted to a value less than the shortest conduction time interval in the absence of sensed R-waves for a period of time longer than the prescribed number of cardiac cycles. In this manner, then, the pacemaker adaptively adjusts its AV time interval, as required, between maximum and minimum values, always attempting to provide a V-pulse just prior to when an R-wave would otherwise occur.

[0025] Thus the present invention may provide an implantable pacemaker that stimulates cardiac tissue at a time in the cardiac cycle that is just prior to when natural depolarization of the cardiac tissue would otherwise cause a cardiac contraction.

[0026] Furthermore, the invention may provide a dual-chamber pacemaker that automatically adjusts its pacemaker-defined AV interval to a value that is just less than the natural conduction time of a patient, thereby assuring that a V-pulse is generated and delivered to the ventricular muscle tissue at a time in the cardiac cycle when such ventricular muscle is not refractory (i.e., prior to the natural depolarization of the ventricular tissue), while still maintaining the approximate cardiac timing set by the natural conduction time, whereby the cardiac output of the patient is maximized.

[0027] The invention may also provide such a pacemaker that decreases the pacemaker-defined AV interval in response to sensing an R-wave (which sensed R-wave evidences a shortened natural conduction time), and that automatically increases the pacemaker-defined AV interval in prescribed increments in response to not sensing an R-wave for a prescribed number of consecutive cardiac cycles (which failure to sense any R-waves may evidence a lengthening of the natural conduction time).

[0028] The invention may be carried into practice in various ways and some embodiments will now be described by way of example with reference to the accompanying drawings, in which:-

FIG. 1 is block diagram of a dual-chamber programmable pacemaker;

FIG. 2 is a block diagram of one embodiment of the control logic of the pacemaker of FIG. 1;

FIG. 3 is a flowchart illustrating the way in which the pacemaker of the present invention works;

FIG. 4 is a more detailed flowchart illustrating the way in which the pacemaker of the present invention works;

FIG. 5 is a flowchart that illustrates one technique for measuring the natural conduction time of a patient; and

FIG. 6 is a flowchart that illustrates another embodiment for determining the natural conduction time of a patient, wherein one of the PR or AR conduction time intervals is measured, and the other is set as a prescribed difference from the measured value.

[0029] As indicated above, the present invention is directed to an implantable dual-chamber pacemaker that automatically adapts or adjusts the AV interval (or PV interval) of the pacemaker in an attempt to maximize the cardiac output of a patient suffering from a cardiomyopathy. In general, the muscle tissue (usually the ventricular muscle tissue) of the heart of a patient suffering from a cardiomyopathy is unable to provide a strong beat (muscle contraction), and is thus not able to efficiently pump much blood with each beat. If a ventricular stimulation pulse (V-pulse) is provided to the heart at the right time in the cardiac cycle, then a stronger beat (muscle contraction) is provided, and the cardiac output (amount of blood pumped by the heart) of the patient increases. The "right time" to provide such a V-pulse in the cardiac cycle is just prior to when the ventricles would beat (depolarize, and hence contract) on their own due to the normal conduction time of the patient, i.e., just prior to the occurrence of an R-wave. To this end, the present invention determines the natural conduction time between a P-wave (evidencing depolarization of the atria) and a subsequent R-wave, or PR interval, and sets the PV interval of the pacemaker to be a prescribed amount less than such PR interval. Alternatively, should the atria of the patient also require stimulation, the invention determines the paced conduction time between an atrial stimulation pulse, (A-pulse) and a subsequent R-wave, or AR interval, and sets the AV interval of the pacemaker to be a prescribed amount less than such AR interval. In this manner, the pacemaker always delivers a V-pulse at the conclusion of the PV or AV intervals, which is less than the natural conduction time (PR or AR interval), and hence before the ventricles attempt to contract on their own.

[0030] Advantageously, the present invention may be implemented using a wide variety of dual-chamber pacemaker configurations and pacemaker hardware. Any pacemaker configuration that allows the pacemaker AV or PV intervals to be automatically set to a value that is a prescribed amount less than the AR or PR conduction-time intervals may be used to implement the invention. The description that follows is only exemplary of one such configuration.

[0031] Referring then to FIG. 1, a block diagram of a dual-chamber pacemaker 10 is illustrated. The pacemaker 10 is coupled to a heart 12 by way of leads 14 and 16. The lead 14 has an electrode 15 that is in contact with one of the atria of the heart, and the lead 16 has an electrode 17 that is in contact with one of the ventricles of the heart. The leads 14 and 16 carry stimulating pulses to the electrodes 15 and 17 from an atrial pulse generator (A-PG) 18 and a ventricular pulse generator (V-PG) 20, respectively. Further, electrical signals

from the atria are carried from the electrode 15, through the lead 14, to the input terminal of an atrial channel sense amplifier (P-AMP) 22; and electrical signals from the ventricles are carried from the electrode 17, through the lead 16, to the input terminal of a ventricular sense channel amplifier (R-AMP) 24.

[0032] A control circuit or control system 26 controls the dual-chamber pacer 10. The control system 26 receives the output signals from the atrial amplifier 22 over signal line 28. Similarly, the control system 26 receives the output signals from the ventricular amplifier 24 over signal line 30. The output signals on signal lines 28 and 30 are generated each time that a P-wave or an R-wave is sensed within the heart 12. The control circuit or system 26 also generates trigger signals that are sent to the atrial pulse generator 18 and the ventricular pulse generator 20 over signal lines 32 and 34, respectively. These trigger signals are generated each time that a stimulation pulse is to be generated by the respective pulse generator 18 or 20. A stimulation pulse generated by the A-PG 18 is referred to as the "A-pulse," and the stimulation pulse generated by the V-PG 20 is referred to as the "V-pulse." During the time that either an A-pulse or V-pulse is being delivered to the heart, the corresponding amplifier, P-AMP 22 and/or R-AMP 24, is typically disabled by way of a blanking signal presented to these amplifiers from the control system over signal lines 36 and 38, respectively. This blanking action prevents the amplifiers 22 and 24 from becoming saturated from the relatively large A-pulse or V-pulse, respectively, that is present at the input terminals of such amplifiers during this time. Such blanking action also prevents the sensing of residual electrical signals that may be present in the muscle tissue as a result of the pacer stimulation, which sensing could falsely be interpreted as P-waves or R-waves.

[0033] Still referring to FIG. 1, the pacer 10 also includes a memory circuit 40 that is coupled to the control system 26 over a suitable data/address bus 42. The memory circuit 40 allows certain control parameters, used by the control system 26 in controlling the operation of the pacemaker, to be programmably stored and modified, as required, in order to customize the pacer's operation to suit the needs of a particular patient. Such data includes the basic timing intervals used during operation of the pacemaker, such as the programmed atrial escape interval (AEI). Further, data sensed during the operation of the pacer may be stored in the memory 40 for later retrieval and analysis.

[0034] A telemetry circuit 44 is further included in the pacer 10. This telemetry circuit 44 is connected to the control system 26 by way of a suitable command/data bus 46. In turn, the telemetry circuit 44, which is included within the implantable pacer 10, may be selectively coupled to an external programming device 48 by means of an appropriate communication link 50, which communication link 50 may be any suitable electromagnetic link, such as an RF (radio frequency) channel. Advantageously, through the external programmer 48 and the communication link 50, desired commands may be sent to the control system 26. Similarly, through this communication link 50 and the programmer 48, data (either held within the control system 26, as in a data latch, or stored within the memory 40), may be remotely received from the pacer 10. In this manner, non-invasive communications can be established from time to time with the implanted pacer 10 from a remote, non-implanted, location. See, e.g., U.S. Patent No. 4,847,617, issued to Silvian, entitled "High Speed Digital Telemetry System for Implantable Devices," incorporated herein by reference.

[0035] The pacer 10 in FIG. 1 is referred to as a dual-chamber pacemaker because it interfaces with both the atria and the ventricles of the heart. Those portions of the pacer 10 that interface with the atria, e.g., the lead 14, the P-wave sense amplifier 22, the A-pulse generator 18, and corresponding portions of the control system 26, are commonly referred to as the atrial channel. Similarly, those portions of the pacer 10 that interface with the ventricles, e.g., the lead 16, the R-wave sense amplifier 24, the V-pulse generator 20, and corresponding portions of the control system 26, are commonly referred to as the ventricular channel.

[0036] In accordance with one embodiment of the present invention, the pacemaker 10 may further include one or more physiological sensors 52 that is connected to the control system 26 of the pacer over a suitable connection line 54. While the sensor 52 is illustrated in FIG. 1 as being included within the pacer 10, it is to be understood that the sensor may also be external to the pacer 10, yet still be implanted within or carried by the patient. A common type of sensor is an activity sensor, such as a piezoelectric crystal, mounted to the case of the pacemaker. Other types of sensors, such as physiologic sensors that sense the oxygen content of blood, respiration rate, pH of blood, and the like, may also be used in lieu of, or in addition to, an activity sensor. The type of sensor, if any, used is not critical to the present invention. Any sensor or combination of sensors capable of sensing body motion or a physiological parameter relatable to the rate at which the heart should be beating can be used. A pacemaker using such sensors is commonly referred to as a "rate-responsive" pacemaker because such a pacemaker adjusts the rate (escape interval) of the pacer in a manner that tracks the physiological needs of the patient.

[0037] Referring next to FIG. 2, a block diagram of one embodiment of the control circuit or system 26 of the pacer 10 is illustrated. It is noted that other embodiments of a control system 26 may also be utilized, such as a microprocessor-based control system. A representative microprocessor-based system is described, for example, in U.S. Patent 4,940,052, entitled "Microprocessor Controlled Rate-Responsive Pacemaker Having Automatic Threshold Adjustment." The '052 patent is assigned to the same assignee as is this applica-

tion.

[0038] The control system shown in FIG. 2 is based on a state machine wherein a set of state registers 60 define the particular state of the pacer at any instant in time. In general, and as an overview of state machine operation, each state, by design, causes a certain activity or function to be carried out. Several states are executed in a sequence during a given cardiac cycle. The sequence of states that is executed in a particular cardiac cycle is determined by the particular events that occur, such as the sensing of a P-wave or an R-wave, as well as the current state, as certain states can only be entered from certain other states. Only one state can exist at any instant of time, although several different state machines (or control systems) may operate in parallel to control diverse functions. For example, the telemetry circuit 44 (FIG. 1) preferably utilizes its own state machine, such as is described in the above-cited patent. The telemetry circuit state machine operates essentially independent of the control system state machine of FIG. 2.

[0039] At the heart of the control system 26 is the state logic 62. It is the state logic that controls the "state" of the state registers 60, and hence the function or operation that will next be carried out by the system. The state logic 62 receives as inputs the current state of the state registers, made available over a state bus 64 (which state bus directs the state of the system to several sections of the control system), as well as other signals indicating the current status of the system or events that have occurred. The output signals from the P-AMP 22 (FIG. 1) and the R-AMP 24 (FIG. 1) are directed to an input decode logic circuit 66. This circuit generates appropriate logic signals "IPW" (Inhibiting P-Wave) and "IRW" (Inhibiting R-Wave) that are selected by a multiplexer 68 and sent to rate-determining logic 70. These signals are also sent to the state logic 62. The function of the rate-determining logic 70 is to determine the rate at which either the IPW or IRW signals are occurring. A signal representative of this rate is sent, as an output signal from the rate determining logic 70, to the state logic 62 over signal line 72. Rate-determining logic 70 further receives a sensor rate signal from the sensor 52 (FIG. 1), and (depending upon the particular state of the system, as defined by the state registers 60, and as made available to the rate-determining logic 70 over the state bus 64) sends a rate signal to the state logic 62 over signal line 72 indicative of this sensor rate.

[0040] Still referring to FIG. 2, a memory control circuit 74 provides the needed interface between the circuits of the control system 26 and the memory 40 (FIG. 1). This memory control circuit may be any conventional memory access circuit that sends or receives data to or from memory at a specified address. Data retrieved from memory 40 may be sent to either the state logic 62 (over signal line(s) 75) or to one or more programmable timers 76 (over signal line(s) 77). Data sent to memory 40 may be either the current state of the system (obtained off of the state bus 64), or other selected signals from the state logic (as made available over signal line(s) 78).

[0041] The programmable timer 76 defines a prescribed time interval, the length of which is set by the signal(s) received from the memory control 74 over signal line(s) 77, and the starting point of which begins coincident with the start of the current state, as obtained from the state bus 64. The timer 76 further generates a time-out (T.O.) signal when this prescribed time interval has elapsed. During the prescribed time interval, the timing function may be reset by a reset signal, typically obtained from the input decode logic 66, although some states (as obtained from the state bus 64) may also effectuate an immediate reset of the timer 76. The time-out signal is sent to time-out decode logic 78. It is the function of the time-out decode logic to generate the appropriate trigger signals that are sent to the A-pulse generator 18 or the V-pulse generator 20 (FIG. 1). Further, an appropriate logic signal(s) is sent to the state logic 62 by the time-out decode logic 78 over signal line(s) 80 in order to notify the state logic that the respective trigger signals have been generated. It is to be understood that while FIG. 2 only shows one programmable timer 76, several such programmable timers may be used, as is required, in order to simultaneously keep track of multiple time intervals.

[0042] An oscillator 82, preferably a crystal-controlled oscillator, generates a basic clock signal C0 that controls the operation of the system logic. This clock signal C0 is sent to clock logic circuits 84, where other appropriate clock signals, such as clock signals C1, C2 and C3, are generated, all derived from the basic clock signal C0. These clock signals are distributed throughout the control system 26 in order to appropriately synchronize the various events and state changes that occur within the pacemaker. The rate of the basic clock signal C0 is not critical to the present invention. In general, a rate of 25-40 Khz for the basic clock rate C0 is adequate. This rate provides a basic time increment of 25-40 microseconds each clock cycle, and this is more than enough time to effectively control the pacemaker operation. If desired, a faster basic clock rate can be used, particularly by the memory control 74, to speed up the data transfer between the control system 26 and the memory 40, although for most pacemaker operations, a fast data transfer rate is not essential.

[0043] In operation, the control system of FIG. 2 starts at an initial state, wherein the state registers 60 assume a prescribed value that defines the initial state. For example, assuming four flip flops are used for the state registers 60, an initial state might be "1000" (hexadecimal "8") wherein the first flip flop assumes a "1" state, and the remaining three flip flops each assume a "0" state. This state may be defined as a V-A Interval (VAI) state wherein a prescribed ventricular-to-atrial (V-A) interval is initiated. For purposes of the present invention, this V-A interval may be considered as the "atrial escape interval," or "AEI." As soon as the memory con-

trol 74 detects that the VAI state has been initiated, as evidenced by the "1000" appearing on the state bus 64, it retrieves from the memory 40 an appropriate data word, previously programmed into the memory 40 from the external programmer 48, or otherwise generated by the state logic 62, that defines the desired length of the AEI. This data word is sent to the programmable timer and sets the length of the time period that is to be measured during the VAI state.

[0044] The timer 76 is essentially just a counter that counts down (or counts up), using a specified clock signal, to the value specified in the data word. When the counting has been completed, and assuming that the counter has not been reset by the occurrence of a P-wave or other sensed event, the counter or timer 76 is said to have "timed-out," and an appropriate time-out signal is generated and sent to the time-out decode logic 78. The decode logic, in turn, recognizes that the current state of the system is the VAI state (as determined by monitoring the state bus 64), and therefore that the AEI has timed-out without any cardiac activity having been sensed. Hence, an A-pulse trigger signal is generated and sent to the A-pulse generator 18, so that the atrium can be stimulated. At the same time, an appropriate logic signal(s) is sent to the state logic 62 over the signal line(s) 80 to alert the state logic to the fact that the timer 76 has timed-out.

[0045] The state logic 62, in response to receiving the signal(s) from the time-out decode logic 78, and also in response to the current VAI state, triggers the next state of the prescribed sequence. For DDD operation, this state is typically a blanking state, or BLANK state, during which the P and R sense amplifiers, 22 and 24, are disabled. Accordingly, the state logic generates appropriate signal(s) on signal lines 36 and 38 to blank the P-wave sense amplifier 22 and the R-wave sense amplifier 24, and also causes the state registers 60 to change to a BLANK state, which state could be defined, for example, by the flip flops of the state registers 62 assuming a "0001" (hex "1") condition. This BLANK state, detected on the state bus 64, causes the memory control circuitry to retrieve an appropriate data word from memory that defines the length of the blanking interval, which data word is loaded into the programmable timer 76. As soon as the timer 76 times out, indicating that the prescribed blanking interval has elapsed, a time-out signal is generated that is sent to the time-out decode logic 78. Upon receipt of this time-out signal, and in response to the current state being a BLANK state, the time-out decode logic 78 sends an appropriate logic signal to the state logic 62. The state logic 62 responds by steering the state registers 62 to assume the next state in the prescribed sequence, which may be, for example, an AV-Interval state.

[0046] At the beginning of the AV-Interval state, another value is loaded into the programmable timer 76, or into an equivalent programmable timer, that defines the length of the pacemaker-defined AV interval, or "AVI." If the timer 76 times out without being reset, indicating that no R-wave has been sensed, the decode-logic generates a V-pulse trigger signal, and notifies the state logic 62 of this event. The state logic, in turn, causes the next appropriate state to be entered, which state may be another blanking state, or BLANK state, similar to the one described above, but having perhaps a different duration. At the conclusion or timing out of this second BLANK state, the next state in the prescribed sequence is initiated, which state may be a refractory (REF) state.

[0047] In the manner described above, the control system 26 assumes one state after another, thereby controlling the operation of the pacemaker. In general, a state is changed when the timer 76, or an equivalent timer, times out, or when a prescribed event occurs. Further, in accordance with the present invention, if a prescribed event occurs, e.g., the occurrence of a P-wave, then the next state may be a PV-Interval state. The PV-Interval state is the same as the AV-Interval state, described above, except that a different value is loaded into the programmable timer 76, which different value defines the length of the PV interval, or "PVI."

[0048] It is noted that the state of the control system could also be changed by receipt of an appropriate command from the telemetry system.

[0049] The control system 26 of FIG. 2 may be realized using dedicated hardware circuits, or by using a combination of hardware and software (or firmware) circuits. The appropriate sequence of states for a given mode of operation, such as DDD (dual-chamber pacing, dual-chamber sensing, dual mode (inhibited and triggered)); DDDR (dual-chamber pacing, dual-chamber sensing, dual mode (inhibited and triggered), rate-responsive); or VDI (ventricular chamber pacing, dual-chamber sensing, inhibited mode), for example, can be defined by appropriate control of the memory control 74 and the state logic 62. These circuit elements, in turn, are most easily controlled through an appropriate software or firmware program that is placed or programmed into the pacemaker memory circuits. The manner of accomplishing such programming is known in the art.

[0050] A detailed description of the various circuits of the control system 26 of FIG. 2 will not be presented herein because all such circuits may be conventional, or may be patterned after known circuits available in the art. Reference is made, for example, to U.S. Patent No. 4,712,555, wherein a state machine-type of operation for a pacemaker is described; U.S. Patent No. 4,788,980, wherein the various timing intervals used within the pacemaker and their interrelationship are more thoroughly described; and U.S. Patent No. 4,944,298, wherein an atrial rate-based programmable pacemaker is described, including a thorough description of the operation of the state logic used to control such a pacemaker.

[0051] Of primary significance to the present invention is the manner in which the AV interval (or PV interval) is

adaptively adjusted as a function of the measured natural conduction time of the patient. The manner in which this is done is illustrated in the flowchart of FIG. 3. In FIG. 3, as well as the other flowcharts presented herein, each main step of the method being described is illustrated as a "box" or "block." Reference numerals are assigned to each block of the flowchart to aid in the description of the invention that follows. Each step of the method, i.e., each block, may be readily carried out by those of skill in the art by programming appropriate "code" in the memory 40, which code causes the necessary control signals to be generated to carry out the desired steps. Equivalent techniques for generating the control signals needed to carry out the prescribed method or sequence may also, of course, be used.

[0052] As seen in FIG. 3, the method starts by setting the initial values needed by the pacemaker to carry out DDD or DDDR pacing (block 102). Such values are, for the most part, no different than those used when performing conventional DDD or DDDR pacing, and include such values as an initial pacing rate (from which an appropriate atrial escape interval is determined), an initial value for the AV interval, blanking period values, maximum pacing rate values, stimulation pulse amplitudes and widths, and the like. In accordance with the present invention, such initial values also include a minimum and maximum value for the AV (or PV) interval, plus a prescribed time difference between the natural conduction time of the patient and the pacemaker-defined AV (or PV) interval. In some embodiments of the invention, it may also be important to specify the difference between the AV interval and a PV interval, where the AV interval is the natural conduction time as measured from the delivery of an A-pulse to the subsequent occurrence of an R-wave, and the PV interval is the natural conduction time as measured from the occurrence of a P-wave to the subsequent occurrence of an R-wave.

[0053] Once the initial values needed to carry out DDD or DDDR pacing have been set, the specified DDD or DDDR pacing is carried out (block 104) in conventional manner, one cardiac cycle at a time, using the programmed values. At some point in a cardiac cycle associated with such DDD or DDDR pacing, an R-wave will occur; or a number of consecutive cardiac cycles will go by without the occurrence of an R-wave. Either event signals a need to determine the natural conduction time of the patient (block 106), so that an appropriate adjustment to the AV (or PV) interval of the pacemaker can be made, as needed (block 108).

[0054] The occurrence of an R-wave indicates the depolarization of the ventricles as a result of a natural or native conduction time that is shorter than the presently existing AV (or PV) interval of the pacemaker. Hence, such event indicates that the pacemaker-defined AV (or PV) interval needs to be decreased. Accordingly, as soon as an R-wave occurs, the natural or native conduction time of the patient, t_{AR} or t_{PR}, is determined. Such natural conduction time is determined as the time interval between the most recent atrial activity, which would be either a P-wave or an A-pulse, and the R-wave. That is, the native or natural conduction time (note, as used herein, "native" and "natural" are used as synonyms) begins with the occurrence of atrial activity, and ends with the occurrence of an R-wave. If the most recent atrial activity was a P-wave, then the conduction time measured is t_{PR}. If the most recent atrial activity was an A-pulse, then the conduction time measured is t_{AR}.

[0055] If an R-wave fails to occur for a prescribed number of cardiac cycles, then that provides an indication that perhaps the natural conduction time has increased, and that there is a need to increase the AV (or PV) interval so that it is not too different than the natural conduction time.

[0056] In either event, once a determination is made that the natural conduction time has either decreased or increased (block 106), the AV (or PV) interval of the pacemaker is then set to a value that is just less than the determined natural conduction time. This is done by either decreasing the AV (or PV) interval when it appears that the natural conduction time has decreased (as is most often the case when an R-wave has been sensed), or by increasing the AV (or PV) interval when it appears that the natural conduction time may have increased (as is most often the case when an R-wave has not been sensed for a prescribed number of cardiac cycles).

[0057] After the AV (or PV) intervals have been set to be less than the determined conduction time t_{AR} (or t_{PR}) at block 108, then a determination is made as to whether DDD or DDDR pacing is to continue (block 110). If not, then the method terminates (block 112). If so, then the method continues (block 104) by performing the DDD or DDDR pacing for the next cardiac cycle using the adjusted values of the AV (or PV) interval.

[0058] Turning next to FIG. 4, a more detailed flowchart is illustrated that shows the preferred technique for determining or measuring the natural conduction time of the patient (block 106 in FIG. 3), and adjusting the AV (or PV) intervals accordingly (block 108 in FIG. 3).

[0059] In FIG. 4, the programmed values needed to carry out DDD or DDDR pacing are programmed into the pacemaker in conventional manner (block 120). In accordance with the present invention, such programmed values include the number of cardiac cycles that must occur without an R-wave before the AV (or PV) interval is increased, the amount of such increase, an initial value for the natural conduction time t_{AR} (or t_{PR}), or an indication of a technique for determining such initial values, the difference X and/or Y between the natural conduction times and the AV (or PV) intervals, and the like (block 122). Once the initial values of t_{AR} or (t_{PR}) have been determined, then the value of the AV (or PV) interval is set to be a specified amount less than t_{AR} or t_{PR} (block 124).

[0060] With the AV (or PV) interval set to an initial value, the DDD or DDDR pacing cycle commences using such value, plus the other programmed values (block 126). If an R-wave is sensed during the pacing cycle (block 126), then that signals that the natural conduction time t_{AR} (or t_{PR}) is shorter than the pacemaker-defined AV (or PV) interval. The occurrence of the R-wave indicates the end of the conduction time t_{AR} (or t_{PR}), and thus permits a measurement of t_{AR} (or t_{PR}) to be completed (block 130). Two different measurement techniques for determining t_{AR} (or t_{PR}) are detailed more fully in FIGS. 5 or 6. The measured value of t_{AR} (or t_{PR}) is then used as a basis for decreasing the AV (or PV) interval (block 132). The AV interval is set to t_{AR}-X, where X is a parameter having a programmable value, a fixed value, or an adaptive value based on a percentage of the heart rate. Similarly, the PV interval is set to t_{PR}-Y, where Y is a parameter having a programmable value, a fixed value, or an adaptive value based on a percentage of the heart rate.

[0061] As is described more fully below in conjunction with FIGS. 5 and 6, in some embodiments of the invention, t_{PR} and t_{AR} are measured separately, and separate values are programmed or otherwise determined for the parameters X and Y. Thus, in such embodiments, t_{PR} and the resulting PV interval, and t_{AR} and the resulting AV interval, are totally independent of each other. In other embodiments, one of t_{AR} or t_{PR} is determined, whichever happens to occur first, and the other is computed as a function of the measured value. In such embodiments, t_{AR} is set to be a prescribed number of milliseconds greater than t_{PR}. In such embodiments, there is thus a prescribed relationship between t_{AR} and t_{PR} and the resulting AV and PV intervals. For most purposes relating to the description of the present invention, one of the AV (or PV) intervals, or one of the conduction times t_{AR} (or t_{PR}), is all that is expressly referenced, and it is assumed that the other can be determined in an appropriate manner.

[0062] After the AV (or PV) interval has been set to its new value based on the most recent measured value of t_{AR} (or t_{PR}) (block 132), a determination is made as to whether the new value of the AV (or PV) interval is less than or equal to a programmed minimum value for the AV (or PV) interval, AV_{MIN} (or PV_{MIN}) (block 134). If so, then the AV (or PV) interval is set to AV_{MIN} (or PV_{MIN}). If not, then the AV (or PV) interval maintains the value previously determined. If DDD (or DDDR) pacing is to continue (block 138), then the next cycle of such pacing continues using the newly set value of the AV (or PV) interval (bock 126).

[0063] Should an R-wave not occur during the pacing cycle (block 128), then a determination is next made (block 140) as to whether a prescribed (programmed) number of cardiac cycles have occurred without the occurrence of an R-wave. If not, then the next cycle begins (block 126). If yes, then that indicates that perhaps the natural conduction time has increased, and that the AV (or PV) interval should also be increased to keep the difference between such natural conduction time and the AV (or PV) intervals to a minimum. Accordingly, the AV (or PV) interval is increased by a prescribed amount, Z (block 142). The value Z may be a fixed value, a programmable value, an adaptive value based on a percentage of heart rate, or a value based on the current AV interval. After the AV (or PV) interval has been increased, a determination is made as to whether the new value of the AV (or PV) interval is greater than or equal to a programmed maximum value for the AV (or PV) interval, AV_{MAX} (or PV_{MAX}) (block 144). If so, then the AV (or PV) interval is set to AV_{MAX} (or PV_{MAX}). If not, then the AV (or PV) interval maintains the value previously determined (at block 142). If DDD (or DDDR) pacing is to continue (block 138), then the next cycle of such pacing continues using the newly set value of the AV (or PV) interval (bock 126).

[0064] The number of cardiac cycles that must occur without the occurrence of an R-wave before the AV (or PV) interval is increased is preferably a programmable number, and may typically be anywhere from 8 to 128 cycles. Alternatively, a specific time interval may be specified, 2-10 minutes, that must elapse without the occurrence of an R-wave before the AV (or PV) interval is increased. The amount Z by which the AV (or PV) interval is incrementally increased is also preferably a programmable value, but could be a fixed value, or an adaptive value. Typical values for Z range from 5-30 msec.

[0065] Referring next to FIG. 5, a flowchart is shown that illustrates one technique for measuring the natural conduction times, t_{AR} and t_{PR}, during one or more cardiac cycles of the heart. The technique shown in FIG. 5 makes an independent measurement of both t_{AR} and t_{PR}. As seen in FIG. 5, at the beginning of the cardiac cycle (block 150), a PR timer and an AR timer are reset (block 152). Such timers, as well as the other timers referenced herein, may be implemented in hardware or software within the control system 26 (FIGS. 1 and 2).

[0066] After resetting such timers, an atrial escape interval (AEI) begins (block 154). If a P-wave is not sensed during the AEI (blocks 156, 174), then an A-pulse is generated (block 158), and the AR timer commences (block 160). Also, the AV interval begins (block 162). If an R-wave occurs during the AV interval (blocks 164, 166), then the AR timer is stopped, and the value of the AR timer represents a measure of the conduction time t_{AR} (block 168). An AR flag is then set (block 170), and the cardiac cycle ends (block 172), having determined t_{AR} during the cycle.

[0067] If the AV interval times out without detecting an R-wave (block 164), then a V-pulse is generated (block 188), and the cardiac cycle ends (block 172), having made no determination of either t_{AR} or t_{PR} during the cycle. Thus, the value of t_{AR} and/or t_{PR} used at the beginning of the next cardiac cycle is retained as the conduction time value used for the preceding cardiac

cycle.

[0068] Should a P-wave be sensed before the AEI times out (blocks 156, 174), than the PR timer is started (block 176). Also, the PV interval is started (block 178). If an R-wave occurs during the PV interval (blocks 189, 182), then the PR timer is stopped, and the value of the PR timer represents a measure of the conduction time t_{PR} (block 184). A PR flag is then set (block 186), and the cardiac cycle ends (block 172), having determined t_{PR} during the cycle.

[0069] It is noted that the AR and PR flags that are set during the cardiac cycle, depending upon whether a P-wave or an A-pulse occurs, may be used during the operation of the pacemaker to steer the adjustment of the AV interval (if the AR flag is set), or the PV interval (if the PR flag is set).

[0070] Turning next to FIG. 6, a flowchart of another embodiment or technique for determining the natural conduction time of a patient is illustrated. The technique shown in FIG. 6 determines just one of t_{AR} or t_{PR}, and the other is set as a prescribed difference from the measured value. Thus, as seen in FIG. 6, once the cardiac cycle begins (block 180), a single timer, designated as the A/P-R Timer, is reset, as is a single flag, designated the A-Flag (block 182). The atrial escape interval (AEI) is started (block 184), and a determination is made as to whether a P-wave is sensed before the timing-out the AEI (blocks 186, 188). If so, then the A/P-R Timer is started (block 190), and the PV interval is started (block 192). While the PV interval is timing-out, a determination is made as to whether an R-wave occurs (blocks 194, 196). If an R-wave does occur during the PV interval, then the A/P-R Timer is stopped (block 214), and a determination is made as to whether the A-Flag is set (block 216). If the A/P-R Timer is not set, then that signals that the A/P-R Timer contains the t_{PR} value, which t_{PR} value may be read from the A/P-R Timer, and the t_{AR} value may be computed therefrom. Typically, t_{AR} is computed as the measured value of t_{PR} less Y_A msec, where Y_A may be a fixed value, a programmed value, or an adaptive value based on a percentage of the heart rate. The cardiac cycle is then completed (block 200) having measured a value of t_{PR} and computed a value of t_{AR} during the cycle.

[0071] If the PV interval times out without sensing an R-wave (blocks 194, 196), then a V-pulse is generated (block 198), and the cardiac cycle terminates (block 200) without having determined a new value for the conduction time t_{AR} or t_{PR}. Hence, the next cardiac cycle starts using the previously determined values of t_{AR} or t_{PR}.

[0072] If the AEI times out without having sensed a P-wave (blocks 186, 188), then the A-Flag is set (block 202), and an A-pulse is generated (block 204). Also, the A/P-R Timer is started (block 206), and the AV interval is started (block 208). While the AV interval is timing-out, a determination is made as to whether an R-wave occurs (blocks 210, 212). If an R-wave does occur during the AV interval, then the A/P-R Timer is stopped (block 214), and a determination is made as to whether the A-Flag is set (block 216). If the A-Flag is set, then that signals that the A/P-R Timer contains the t_{AR} value, which t_{AR} value may be read from the A/P-R Timer, and the t_{PR} value may be computed therefrom. Typically, t_{PR} is computed as the measured value of t_{AR} minus Y_B msec, where Y_B may be a fixed value, a programmed value, or an adaptive value based on a percentage of the heart rate. The cardiac cycle is then completed (block 200) having measured a value of t_{AR} and computed a value of t_{PR} during the cycle.

[0073] If the AV interval times out without sensing an R-wave (blocks 210, 212), then a V-pulse is generated (block 198), and the cardiac cycle terminates (block 200) without having determined a new value of the conduction times t_{AR} or t_{PR}. Hence, the next cardiac cycle starts using the previously determined values of t_{AR} or t_{PR}.

[0074] Thus it is seen that the present invention provides an implantable pacemaker that stimulates cardiac tissue at a time in the cardiac cycle that is just prior to when natural depolarization of the cardiac tissue would otherwise cause a cardiac contraction.

[0075] As further described above, it is seen that the invention provides a dual-chamber pacemaker, and method of operating such a dual-chamber pacemaker, that automatically adjusts the pacemaker-defined AV interval to a value that is just less than the natural conduction time of the patient. Such action advantageously assures that a V-pulse is generated and delivered to the ventricular muscle tissue at a time in the cardiac cycle when such ventricular muscle is not refractory (i.e., prior to the natural depolarization of the ventricular tissue), while still maintaining the approximate cardiac timing set by the natural conduct ion time, thereby maximizing the cardiac output of the patient.

[0076] As also described above, it is seen that the invention provides a dual-chamber pacemaker that decreases the pacemaker-defined AV interval in response to sensing an R-wave (which sensed R-wave evidences a shortened natural conduction time), and that automatically increases the pacemaker-defined AV interval in prescribed increments in response to not sensing an R-wave for a prescribed number of consecutive cardiac cycles (which failure to sense any R-waves may evidence a lengthening of the natural conduction time). Thus, advantageously, the pacemaker-defined AV interval is most always set to a value that is just somewhat less than the natural conduction time, regardless of whether the natural conduction time is increasing or decreasing, and the cardiac output of the patient is maximized.

Claims

1. A dual-chamber pacemaker for controlling ventricular pacing in order to increase cardiac output in a

patient suffering from a cardiomyopathy by preemptively stimulating the ventricular channel, comprising: an atrial channel and a ventricular channel; an atrial sense amplifier that senses a P-wave in the atrial channel, the P-wave representing natural atrial activity; a ventricular sense amplifier that senses an R-wave in the ventricular channel, the R-wave representing natural ventricular activity; pulse generator means for generating a ventricular stimulation pulse (V-pulse) in the ventricular channel and an atrial stimulation pulse (A-pulse) in the atrial channel, the sensing of a P-wave or the generating of an A-pulse, whichever occurs first, representing atrial activity; and timing means arranged to define an AV time interval as the time interval between atrial activity and the generation of a V-pulse, characterised in that the timing means further being arranged to measure a natural conduct ion time interval as the time period between atrial activity and the sensing of an R-wave; the timing means also being arranged to set automatically the AV time interval to a value that is less than the natural conduction time interval, whereby the pulse generator generates the V-pulse prior to the occurrence of natural ventricular activity in order to stimulate preemptively the ventricular channel, thereby increasing cardiac output.

2. A pacemaker as claimed in Claim 1, further comprising means for setting the AV interval to a value that, during generation of a ventricular stimulation pulse, is always less than the natural conduction time interval by a prescribed amount.

3. A pacemaker a claimed in Claim 1 or Claim 2, in which the timing means includes measurement means for measuring the natural conduction time, t_{PR} or t_{AR}, of a heart to which the pacemaker is coupled, where t_{PR} represents the natural conduction time following a natural atrial event (P-wave), and t_{AR} represents the natural conduction time of the heart following an atrial stimulation pulse (A-pulse); and the timing means is arranged to set automatically a PV interval for use by the pacemaker following a P-wave, and an AV interval for use by the pacemaker following an A-pulse, to a prescribed amount less than the natural conduction time, t_{PR} or t_{AR}, respectively, the PV and AV intervals being used by the timing means to define the time period between a P-wave and a V-pulse, and between an A-pulse and a V-pulse, respectively, during the operation of the pacemaker.

4. A pacemaker as claimed in Claim 3, in which the timing means automatically adjusts the PV and AV intervals to make them a prescribed amount less than the PV or AV interval used by the pacemaker in a most recent cardiac cycle in the event an R-wave is sensed during the most recent pacing cycle.

5. A pacemaker as claimed in Claim 4, in which the timing means further automatically adjusts the PV and AV intervals to make them a prescribed amount greater than the PV or AV interval used by the pacemaker in a most recent cardiac cycle, up to a predetermined maximum PV or AV interval, in the event no R-wave is sensed for a specified number of consecutive prior cardiac cycles.

6. A pacemaker as claimed in any of Claims 3 to 5, in which the measurement means includes means for measuring one of the t_{PR} or t_{AR} natural conduction times, depending upon which of the A-pulse or P-wave occurs first, and means for computing the other of the t_{PR} or t_{AR} natural conduction times as a function of the measured one of the t_{PR} or t_{AR} natural conduction times.

7. A pacemaker as claimed in Claim 6, in which the means for computing the other of the t_{PR} or t_{AR} natural conduction times once one has been measured comprises means for defining t_{AR} to be a prescribed amount greater than t_{PR}, whereby once one of the t_{PR} or t_{AR} natural conduction times has been measured, the other of the t_{PR} or t_{AR} natural conduction times is computed to be less than or greater than the measured value of t_{PR} or t_{AR} by the prescribed amount.

8. A pacemaker as claimed in any of Claims 3 to 5, in which the measurement means includes means for measuring both t_{PR} and t_{AR}, where t_{PR} is measured as the time interval between the occurrence of a P-wave and a subsequent R-wave, and t_{AR} is measured as the time interval between the generation of an A-pulse and a subsequent R-wave.

9. A pacemaker as claimed in Claim 3, in which the timing means sets the PV interval to be a first prescribed amount less than t_{PR}, and sets the AV interval to be a second prescribed amount less than t_{AR}.

10. A pacemaker as claimed in Claim 9, in which the first prescribed amount is the same as the second prescribed amount, whereby the difference between the PV interval and the AV interval is the same as the difference between t_{AR} and t_{PR}.

11. A pacemaker as claimed in Claim 9, in which the first prescribed amount and the second prescribed amount are computed as a function of the most recent measured values of t_{PR} and t_{AR}, respectively.

Patentansprüche

1. Zweikammer-Schrittmacher zur Kontrolle der ventrikulären Aktivität, um durch eine vorzeitige Stimulation des ventrikulären Kanals die kardiale Leistung eines unter Kardiomyopathie leidenden Patienten zu steigern, enthaltend: einen atrialen Kanal und einen ventrikulären Kanal; einen atrialen Sensorverstärker, welcher eine P-Welle im atrialen Kanal registriert, wobei die P-Welle natürliche atriale Aktivität anzeigt; einen ventrikulären Sensorverstärker, welcher eine R-Welle im ventrikulären Kanal registriert, wobei die R-Welle natürliche ventrikuläre Aktivität anzeigt; Mittel zur Generierung von Pulsen zur Erzeugung eines ventrikulären Stimulationsimpulses (V-Puls) im ventrikulären Kanal und eines atrialen Stimulationsimpulses (A-Puls) im atrialen Kanal, wobei das frühere der baden Ereignisse der Registrierung einer P-Welle und der Erzeugung eines A-Pulses atriale Aktivität anzeigt; und Mittel zur Zeitsteuerung, welche ein AV-Zeitintervall als das Zeitintervall zwischen atrialer Aktivität und der Erzeugung eines V-Pulses definieren; **dadurch gekennzeichnet, daß** die Mittel zur Zeitsteuerung weiterhin so ausgestaltet sind, daß sie ein natürliches Leitungszeitintervall als die Zeitdauer zwischen atrialer Aktivität und der Registrierung einer R-Welle messen; die Mittel zur Zeitsteuerung darüber hinaus so ausgestaltet sind, daß sie automatisch das AV-Zeitintervall auf einen Wert kleiner als die natürliche Leitungszeit setzen, wodurch der Pulsgenerator vor dem Auftreten natürlicher ventrikulärer Aktivität einen V-Puls erzeugt, um vorauseilend den ventrikulären Kanal zu stimulieren, so daß die Herzleistung ansteigt.

2. Schrittmacher nach Anspruch 1, **dadurch gekennzeichnet, daß** er Mittel enthält, welche das AV-Intervall auf einen Wert setzen, welcher während der Erzeugung eines ventrikulären Stimulationsimpulses immer um einen vorgeschriebenen Betrag kleiner ist als die natürliche Leitungszeit.

3. Schrittmacher nach einem der Ansprüche 1 und 2, **dadurch gekennzeichnet, daß** die Mittel zur Zeitsteuerung Mittel zur Messung der natürlichen Leitungszeit t_{PR} oder t_{AR} des Herzens, an das der Schrittmacher gekoppelt ist, enthalten, wobei t_{PR} die natürliche Leitungszeit nach einem natürlichen atrialen Ereignis (P-Welle) repräsentiert und t_{AR} die natürliche Leitungszeit des Herzens nach einer atrialen Stimulation (A-Puls) repräsentiert, und daß die Zeitsteuerung weiterhin so eingerichtet ist, daß sie automatisch ein PV-Intervall, welches vom Schrittmacher nach dem Auftreten einer P-Welle verwendet wird, sowie ein AV-Intervall, welches vom Schrittmacher nach dem Auftreten eines A-Pulses verwendet wird, auf einen Wert setzt, der um einen vorgeschriebenen Betrag kleiner ist als die natürliche Leitungszeit t_{PR} bzw. t_{AR}, wobei die PV- und AV-Intervalle von der Zeitsteuerung verwendet werden, um die Zeitdauer zwischen einer P-Welle und einem V-Puls bzw. einem A-Puls und einem V-Puls während des Betriebs des Schrittmachers zu definieren.

4. Schrittmacher nach Anspruch 3, **dadurch gekennzeichnet, daß** die Zeitsteuerung automatisch die PV- und AV-Intervalle auf einen Wert anpaßt, welcher um einen vorgegebenen Betrag kleiner als das vom Schrittmacher im letzten vorhergehenden kardialen Zyklus verwendete PV- oder AV-Intervall ist, falls während des letzten vorhergegangenen Schrittmacherzyklus eine R-Welle registriert wurde.

5. Schrittmacher nach Anspruch 4, **dadurch gekennzeichnet, daß** die Zeitsteuerung weiterhin die PV- und AV-Intervalle automatisch auf einen Wert anpaßt, welcher um einen vorgeschriebenen Betrag größer als das vom Schrittmacher im letzten vorhergegangenen Herzzyklus verwendete PV- oder AV-Intervalle aber nicht größer als ein vorgegebener maximaler Wert für das PV- oder AV-Intervall ist, wenn für eine vorgegebene Anzahl aufeinander folgender vorhergegangener kardialer Zyklen keine R-Welle registriert worden ist.

6. Schrittmacher nach einem der Ansprüche 3 bis 5, **dadurch gekennzeichnet, daß** er Mittel zur Messung von einer der natürlichen Leitungszeichen t_{PR} oder t_{AR} enthält, je nach dem, ob der A-Puls oder die P-Welle zuerst auftritt, sowie Mittel zur Berechnung der jeweils anderen der natürlichen Leitungszeiten t_{PR} oder t_{AR} als Funktion der gemessenen der beiden natürlichen Leitungszeiten t_{PR} oder t_{AR}.

7. Schrittmacher nach Anspruch 6, **dadurch gekennzeichnet, daß** die Mittel zur Berechnung der jeweils anderen der natürlichen Leitungszeiten t_{PR} oder t_{AR} nach Messung der einen dieser Leitungszeiten Mittel enthalten, mit denen t_{AR} um einen vorgeschriebenen Betrag größer als t_{PR} definiert werden kann, so daß wenn eine der beiden natürlichen Leitungszeiten t_{PR} oder t_{AR} gemessen wurde, die andere der natürlichen Leitungszeiten t_{PR} oder t_{AR} als um einen vorgegebenen Betrag kleiner oder größer als der gemessene Wert t_{PR} oder t_{AR} berechnet wird.

8. Schrittmacher nach einem der Ansprüche 3 bis 5, **dadurch gekennzeichnet, daß** er Mittel zur Messung von sowohl t_{PR} als auch t_{AR} enthält, wobei t_{PR} das gemessene Zeitintervall zwischen dem Auftreten einer P-Welle und einer nachfolgenden R-Welle ist, und wobei t_{AR} das gemessene Zeitintervall zwischen der Erzeugung eines A-Pulses und einer

nachfolgenden R-Welle ist.

9. Schrittmacher nach Anspruch 3, **dadurch gekennzeichnet, daß** das Mittel zur Zeitsteuerung das PV-Intervall auf einen Wert einstellt, welcher um einen ersten vorgegebenen Betrag kleiner als t_{PR} ist, und daß es das AV-Intervall auf einen Wert einstellt, welcher um einen zweiten vorgegebenen Betrag kleiner als t_{AR} ist.

10. Schrittmacher nach Anspruch 9, **dadurch gekennzeichnet, daß** der erste vorgegebene Betrag gleich groß ist wie der zweite vorgegebene Betrag, so daß die Differenz zwischen dem PV-Intervall und dem AV-Intervall die gleiche ist wie die Differenz zwischen t_{PR} und t_{AR}.

11. Schrittmacher nach Anspruch 9, **dadurch gekennzeichnet, daß** der erste vorgegebene Betrag und der zweite vorgegebene Betrag als Funktion der zuletzt gemessenen Werte für t_{PR} bzw. t_{AR} berechnet werden.

Revendications

1. Un stimulateur cardiaque à deux chambres pour commander la stimulation ventriculaire afin d'augmenter le débit cardiaque chez un patient qui souffre d'une cardiomyopathie en stimulant préalablement le canal ventriculaire, qui comprend: un canal auriculaire et un canal ventriculaire; un amplificateur de détection auriculaire qui détecte une onde P dans le canal auriculaire l'onde P représentant une activité auriculaire naturelle; un amplificateur de détection ventriculaire qui détecte une onde R dans le canal ventriculaire, l'onde R représentant une activité ventriculaire naturelle; un moyen générateur d'impulsions pour engendrer une impulsion (impulsion V) de stimulation ventriculaire dans le canal ventriculaire et une impulsion (impulsion A) de stimulation auriculaire dans le canal auriculaire, le premier des deux événements: la détection d'une onde P ou la génération d'une onde A, représentant une activité auriculaire; et un moyen de cadencement agencé pour définir un intervalle de temps AV comme intervalle de temps entre une activité auriculaire et la génération d'une impulsion V, caractérisé en ce que le moyen de cadencement est en outre agencé pour mesurer un intervalle de temps de conduction naturelle en tant que laps de temps entre une activité auriculaire et la détection d'une onde R; le moyen de cadencement étant de plus agencé pour régler automatiquement l'intervalle de temps AV à une valeur qui est inférieure à l'intervalle de temps de conduction naturelle, de sorte que le générateur d'impulsions engendre l'impulsion V avant l'apparition de l'activité ventriculaire naturelle afin de stimuler préalablement le canal ventriculaire, en augmentant ainsi le débit cardiaque.

2. Un stimulateur cardiaque selon la revendication 1, qui comprend en outre un moyen de réglage de l'intervalle AV à une valeur qui est toujours inférieure d'un laps de temps prescrit, pendant une génération d'une impulsion de stimulation ventriculaire, à l'intervalle de temps de conduction naturelle.

3. Un stimulateur cardiaque selon la revendication 1 ou la revendication 2, dans lequel le moyen de cadencement inclut un moyen de mesure pour mesurer le temps de conduction naturelle, t_{PR} ou t_{AR}, d'un coeur auquel le stimulateur cardiaque est coupé, où t_{PR} représente le temps de conduction naturelle après un événement auriculaire naturel (onde P) et t_{AR} représente le temps de conduction naturel du coeur après une impulsion de stimulation auriculaire (impulsion A); et le moyen de cadencement est agencé pour régler automatiquement à un laps de temps prescrit inférieur au temps de conduction naturelle t_{PR} ou t_{AR}, respectivement, un intervalle PV à utiliser par le stimulateur cardiaque après une onde P, et un intervalle AV à utiliser par le stimulateur cardiaque après une impulsion A, les intervalles PV et AV étant utilisés par le moyen de cadencement pour définir le laps de temps entre une onde P et une impulsion V, et entre une impulsion A et une impulsion V, respectivement, au cours du fonctionnement du stimulateur cardiaque.

4. Un stimulateur cardiaque selon la revendication 3, dans lequel le moyen de cadencement ajuste automatiquement, dans le cas où une onde R est détectée pendant le cycle de stimulation le plus récent, les intervalles PV et AV pour qu'ils soient inférieurs d'un laps de temps prescrit à l'intervalle PV ou AV utilisé par le stimulateur cardiaque dans un cycle cardiaque le plus récent.

5. Un stimulateur cardiaque selon la revendication 4, dans lequel le moyen de cadencement ajuste en outre, automatiquement les intervalles PV et AV pour les rendre supérieurs d'un laps de temps prescrit à l'intervalle PV ou AV utilisé par le stimulateur cardiaque dans un cycle cardiaque le plus récent, jusqu'à un intervalle PV ou AV maximal prédéterminé, dans le cas où aucune onde R n'est détectée pendant un nombre spécifié de cycles cardiaques antérieurs consécutifs.

6. Un stimulateur cardiaque selon l'une quelconque des revendications 3 à 5, dans lequel le moyen de mesure inclut un moyen de mesure de l'un des temps t_{PR} ou t_{AR} de conduction naturelle, selon que c'est l'impulsion A ou l'onde P qui apparaît en pre-

mier lieu, et un moyen de calcul de l'autre des temps t_{PR} ou t_{AR} de conduction naturelle en fonction de celui des temps t_{PR} ou t_{AR} de conduction naturelle qui a été mesuré.

7. Un stimulateur cardiaque selon la revendication 6, dans lequel le moyen de calcul de l'autre des temps t_{PR} ou t_{AR} de conduction naturelle dès lors que l'un d'eux a été mesuré comprend un moyen de définition de t_{AR} pour qu'il soit supérieur d'un laps de temps prescrit à t_{PR} de sorte que, dès lors que l'un des temps t_{PR} ou t_{AR} de conduction naturelle a été mesuré, l'autre des temps t_{PR} ou t_{AR} de conduction naturelle est calculé de manière à être inférieur ou supérieur du laps de temps prédéterminé à la valeur mesurée de t_{PR} ou t_{AR}.

8. Un stimulateur cardiaque selon l'une quelconque des revendications 3 à 5, dans lequel le moyen de mesure inclut un moyen de mesure tant de t_{PR} que de t_{AR}, où t_{PR} est mesuré comme l'intervalle de temps entre l'apparition d'une onde P et celle d'une onde R ultérieure, et t_{AR} est mesuré comme l'intervalle de temps entre la génération d'une impulsion A et celle d'une onde R ultérieure.

9. Un stimulateur cardiaque selon la revendication 3, dans lequel le moyen de cadencement règle l'intervalle PV pour qu'il soit inférieur d'un premier laps de temps prescrit à t_{PR} et règle l'intervalle AV pour qu'il soit inférieur d'un deuxième laps de temps prescrit à t_{AR}.

10. Un stimulateur cardiaque selon la revendication 9, dans lequel le premier laps de temps prescrit est le même que le deuxième laps de temps prescrit, de sorte que la différence entre l'intervalle PV et l'intervalle AV est la même que la différence entre t_{AR} et t_{PR}.

11. Un stimulateur selon la revendication 9, dans lequel la première quantité prescrite et la deuxième quantité prescrite sont calculées en fonction des valeurs mesurées les plus récentes de t_{PR} et t_{AR}, respectivement.

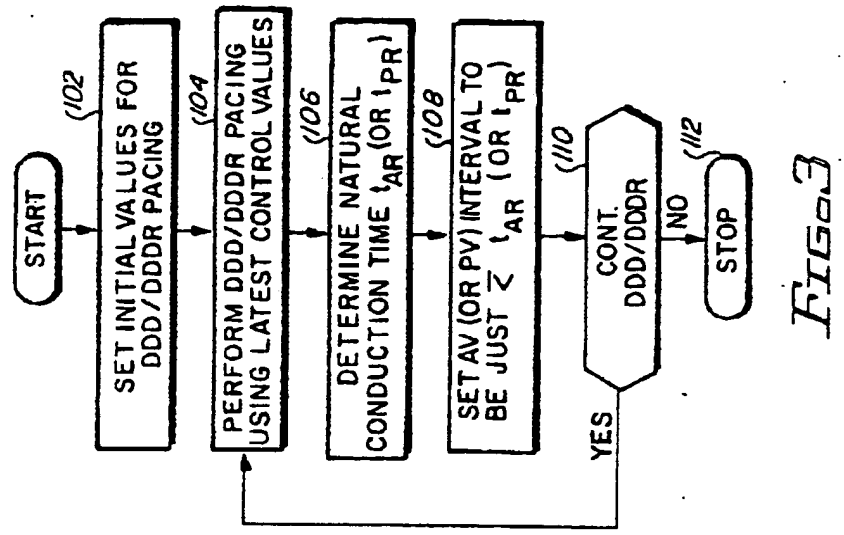
START
102
SET INITIAL VALUES FOR DDD/DDDR PACING
104
PERFORM DDD/DDDR PACING USING LATEST CONTROL VALUES
106
DETERMINE NATURAL CONDUCTION TIME t_{AR} (OR t_{PR})
108
SET AV (OR PV) INTERVAL TO BE JUST < t_{AR} (OR t_{PR})
110
CONT. DDD/DDDR
YES
NO
112
STOP

Fig. 3

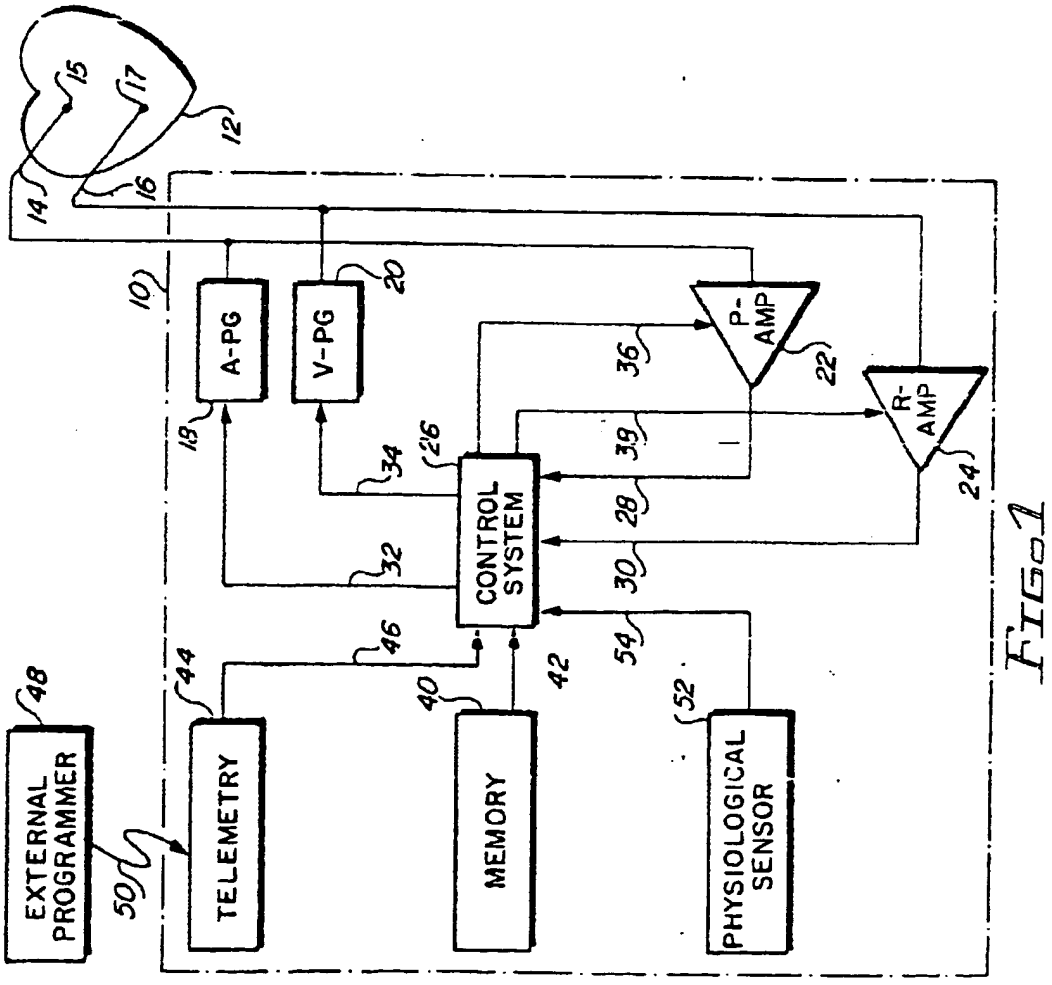
15
17
12
14
16
10
A-PG
V-PG
20
18
34
26
P-AMP
22
36
R-AMP
24
39
28
CONTROL SYSTEM
32
30
46
54
42
40
52
44
48
EXTERNAL PROGRAMMER
50
TELEMETRY
MEMORY
PHYSIOLOGICAL SENSOR

Fig. 1

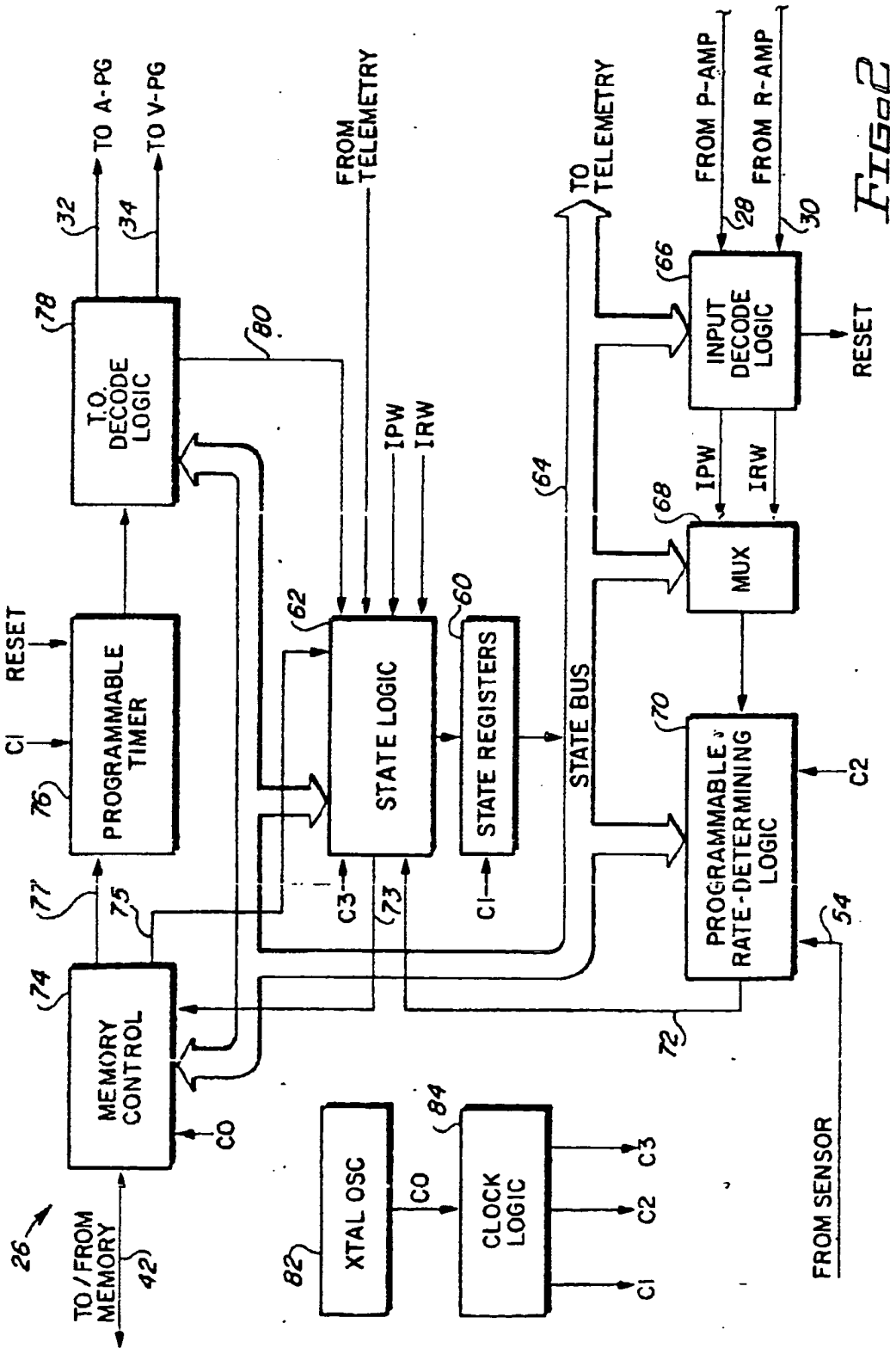
TO A-PG
TO V-PG
FROM TELEMETRY
TO TELEMETRY
FROM P-AMP
FROM R-AMP
32
34
28
30
78
T.O. DECODE LOGIC
80
66
INPUT DECODE LOGIC
RESET
IPW
IRW
64
68
MUX
RESET
CI
76
PROGRAMMABLE TIMER
62
STATE LOGIC
60
STATE REGISTERS
STATE BUS
70
PROGRAMMABLE RATE-DETERMINING LOGIC
C2
77'
75
C3
73
CI
74
MEMORY CONTROL
CO
54
72
FROM SENSOR
26
TO/FROM MEMORY
42
82
XTAL OSC
CO
84
CLOCK LOGIC
C3
C2
CI

Fig. 2

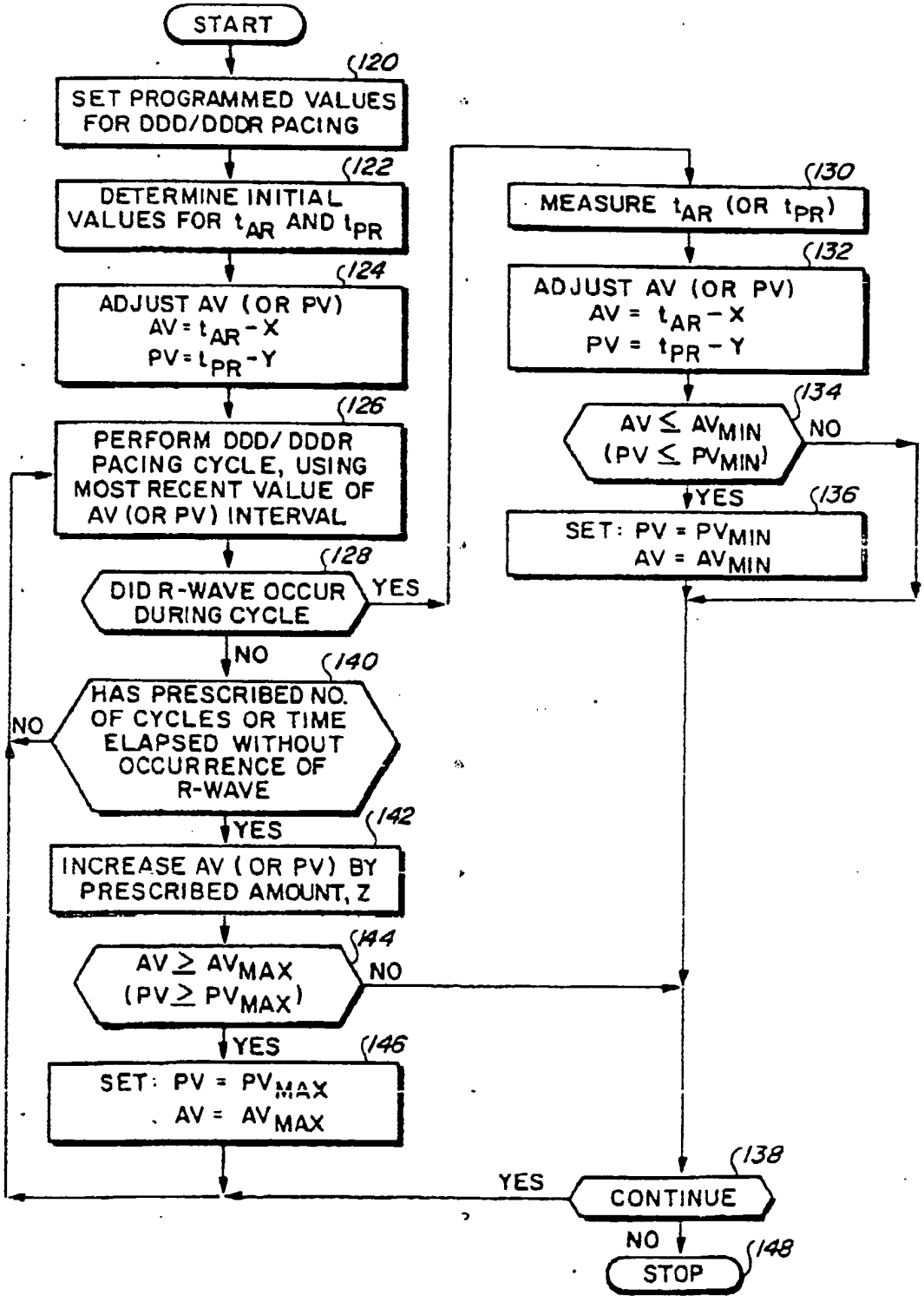
START
120
SET PROGRAMMED VALUES FOR DDD/DDDR PACING
122
DETERMINE INITIAL VALUES FOR t_{AR} AND t_{PR}
124
ADJUST AV (OR PV)
$AV = t_{AR} - X$
$PV = t_{PR} - Y$
126
PERFORM DDD/DDDR PACING CYCLE, USING MOST RECENT VALUE OF AV (OR PV) INTERVAL
128
DID R-WAVE OCCUR DURING CYCLE
YES
NO
130
MEASURE t_{AR} (OR t_{PR})
132
ADJUST AV (OR PV)
$AV = t_{AR} - X$
$PV = t_{PR} - Y$
134
$AV \leq AV_{MIN}$
($PV \leq PV_{MIN}$)
NO
YES
136
SET: $PV = PV_{MIN}$
$AV = AV_{MIN}$
140
HAS PRESCRIBED NO. OF CYCLES OR TIME ELAPSED WITHOUT OCCURRENCE OF R-WAVE
NO
YES
142
INCREASE AV (OR PV) BY PRESCRIBED AMOUNT, Z
144
$AV \geq AV_{MAX}$
($PV \geq PV_{MAX}$)
NO
YES
146
SET: $PV = PV_{MAX}$
$AV = AV_{MAX}$
138
CONTINUE
YES
NO
148
STOP

FIG. 4

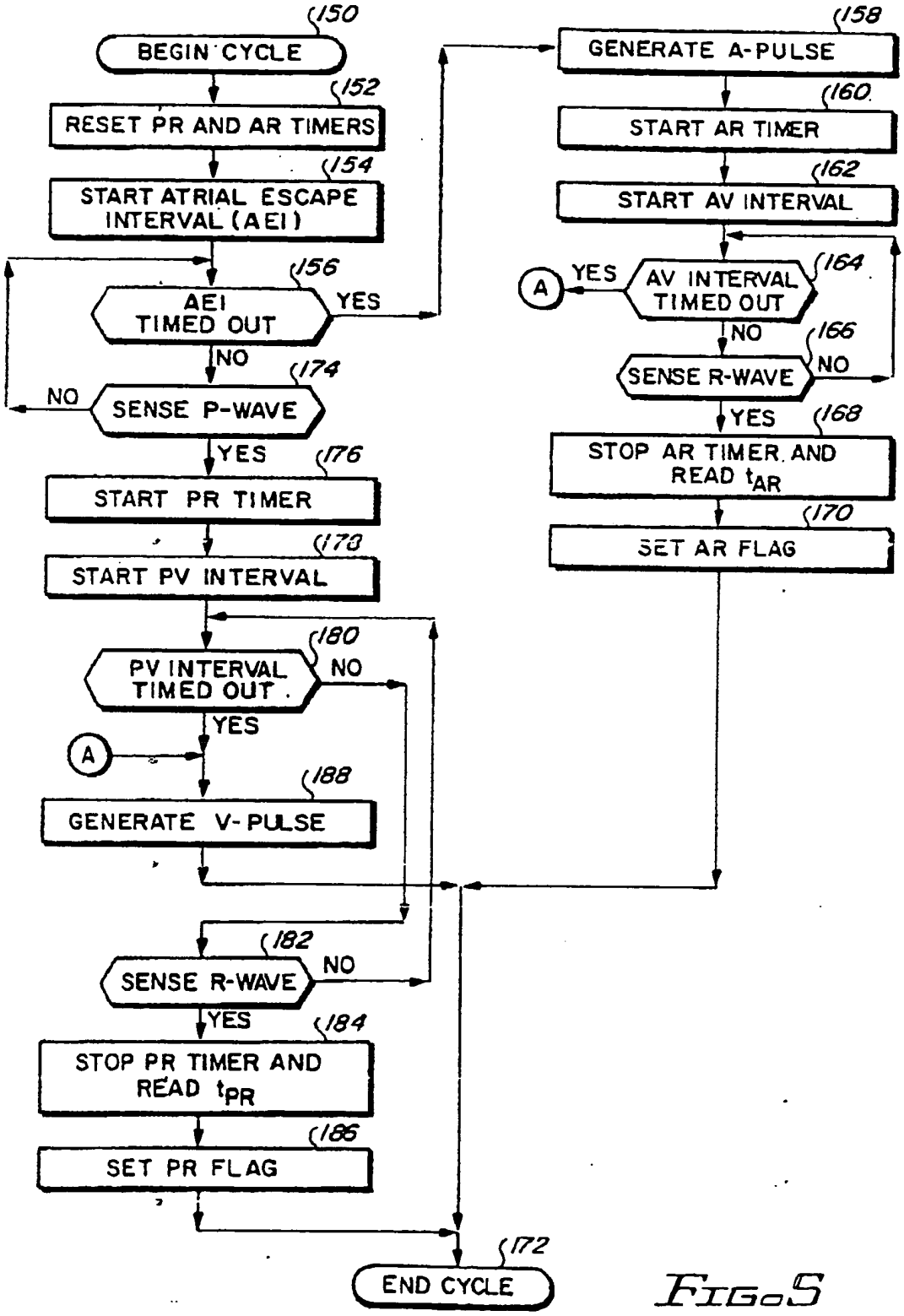
150
BEGIN CYCLE
152
RESET PR AND AR TIMERS
154
START ATRIAL ESCAPE INTERVAL (AEI)
156
AEI TIMED OUT
YES
NO
174
NO
SENSE P-WAVE
YES
176
START PR TIMER
178
START PV INTERVAL
180
PV INTERVAL TIMED OUT
NO
YES
A
188
GENERATE V-PULSE
182
SENSE R-WAVE
NO
YES
184
STOP PR TIMER AND READ t_{PR}
186
SET PR FLAG
172
END CYCLE
158
GENERATE A-PULSE
160
START AR TIMER
162
START AV INTERVAL
A
YES
164
AV INTERVAL TIMED OUT
NO
166
SENSE R-WAVE
NO
YES
168
STOP AR TIMER AND READ t_{AR}
170
SET AR FLAG

FIG. 5

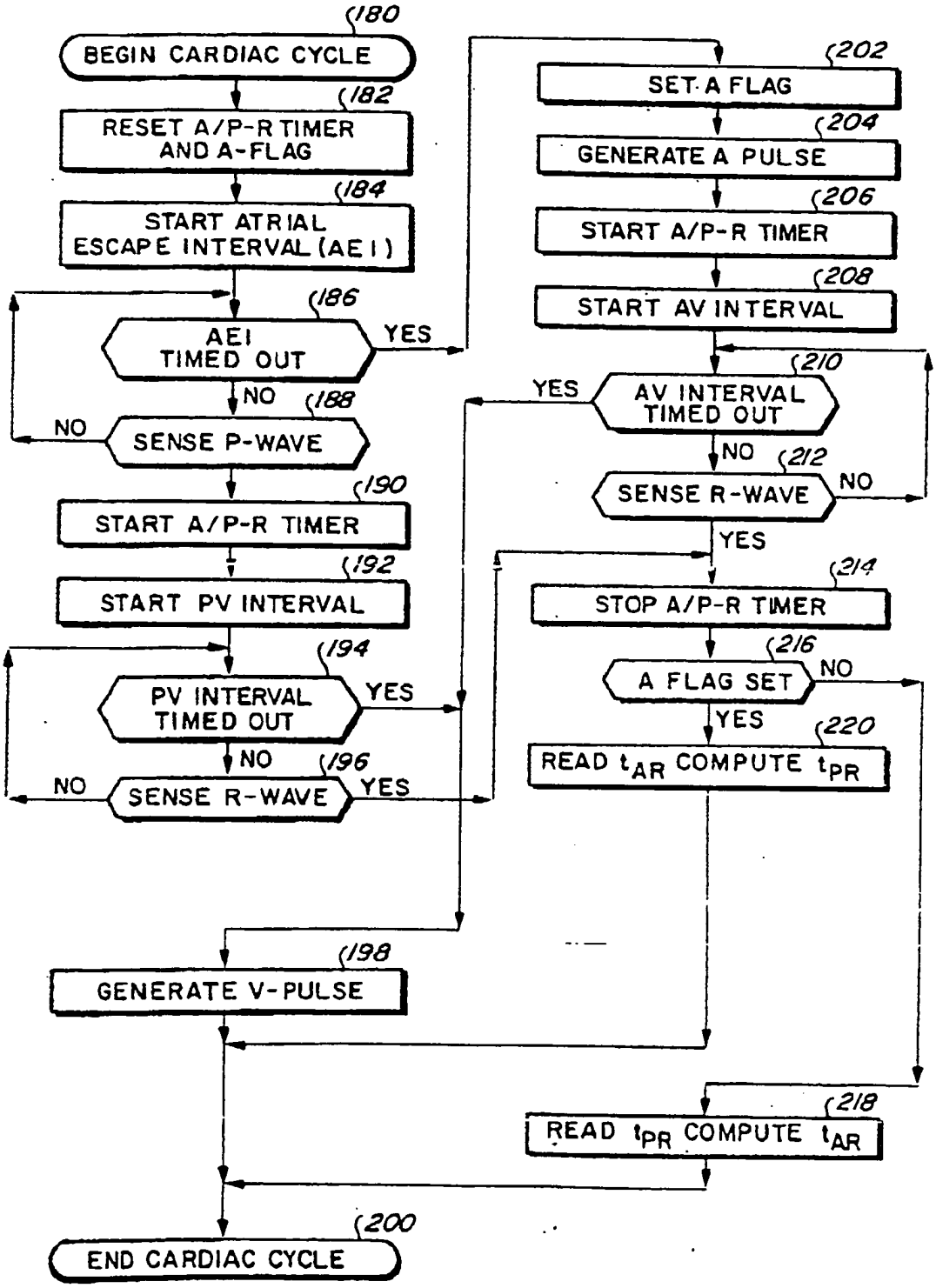
180
BEGIN CARDIAC CYCLE
182
RESET A/P-R TIMER AND A-FLAG
184
START ATRIAL ESCAPE INTERVAL (AEI)
186
AEI TIMED OUT
YES
NO
188
NO
SENSE P-WAVE
190
START A/P-R TIMER
192
START PV INTERVAL
194
PV INTERVAL TIMED OUT
YES
NO
196
NO
SENSE R-WAVE
YES
198
GENERATE V-PULSE
202
SET A FLAG
204
GENERATE A PULSE
206
START A/P-R TIMER
208
START AV INTERVAL
210
YES
AV INTERVAL TIMED OUT
NO
212
SENSE R-WAVE
NO
YES
214
STOP A/P-R TIMER
216
A FLAG SET
NO
YES
220
READ t_{AR} COMPUTE t_{PR}
218
READ t_{PR} COMPUTE t_{AR}
200
END CARDIAC CYCLE

FIG-6